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Energy Procedia 37 (2013) 4833 – 4842

Energy Procedia

GHGT-11

Features Events and Processes (FEPs) and Scenario Analysis in the Field of CO_2 Storage

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Abstract

Analysis of Features Events and Processes (FEPs) has aided the development of scenarios for the future evolution of CO_2 storage sites in a number of countries. However, in different CO_2 storage projects the FEP analysis and scenario development has followed different approaches. To determine the relative advantages of these different approaches, as a basis for developing a refined methodology, we reviewed the development and application of databases and lists of FEPs in CO_2 storage projects throughout the world.

Keywords: Features Events and Processes, FEPs, FEP analysis, scenario

1. Introduction

Features, Events and Processes (FEPs) are used to describe and analyse the characteristics of a system of interest in a structured and transparent fashion. In recent years the approach has been used widely in the field of underground CO_2 storage (e.g. Wildenborg et al. [1], [2]; Savage et al. [3]; Wilson and Monea, [4]; Maul et al. [5]; Stenhouse et al. [6]; Chadwick et al. [7]; Ayash et al. [8]; Hnottavange-Telleen et al. [9]). In CO_2 storage, the 'system' could be the entire storage system (reservoir, caprock, overburden, sideburden, underburden, wells etc.), or some component of this system, such as a well and its immediate

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doi:10.1016/j.egypro.2013.06.393

surroundings. Many slightly different formal definitions of the term 'FEP' have been proposed (e.g. IAEA, [10]; Wilson and Monea [4]), but fundamentally:

- A 'Feature' is a physical component of a system (in CO_2 storage, 'faults' or 'cap rock' would be features of the system), or a physical entity that influences a system.
- An 'Event' is a process that influences system evolution over a time period that is short compared to the time frame being considered (usually an earthquake would be considered an 'event').
- A 'Process' is a dynamic interaction between 'Features', which may operate over any particular time interval of interest (formation fluid displacement would normally be considered a 'process').

The definitions of 'Events' and 'Processes' overlap. The time frame being considered will largely determine whether or not a phenomenon is classified as an 'Event' or a 'Process'.

'FEP analysis' is the systematic, structured identification of FEPs that should be included in an assessment of system performance, and the important interactions between these FEPs. The FEPs to be considered and the ways in which they are evaluated will depend upon the nature of the assessment.

To support the use of FEPs in CO_2 storage projects, Quintessa developed the 'on-line Generic CO_2 FEP Database' (Savage et al. [3]; Maul et al. [5]; Stenhouse et al. [6]; Walke et al. [11]), which may be accessed freely at: http://www.quintessa.org/co2fepdb/ . Beginning in 2005, Quintessa was commissioned by the Research Institute of Innovative Technology for the Earth (RITE), via a sub-contract with Mitsubishi Materials Corporation (MMC), to produce a Japanese language version of this database with enhanced functions, called the 'RITE-DB'. To help RITE evaluate how best to use the RITE-DB in future projects, FEP databases and scenario development approaches that have been used in CO_2 storage projects throughout the world were reviewed. The outcomes of this review are reported here.

2. Nature of Generic FEP Databases

Generic FEP databases are not specific to any particular CO_2 storage concept or location. Their purposes are to: (1) aid structured development of models and scenarios; (2) act as audit tools for scenarios and models (especially system-level models); (3) provide knowledge bases for storage studies; and (4) to stimulate discussions among experts. The FEPs in such generic databases are defined very generally, so that collectively they should describe all the phenomena that may occur within a CO_2 storage system or that may impact upon it. The most widely used generic FEP list is Quintessa's freely available on-line CO_2 FEP database (Walke et al. [11]), which has been accessed by almost 1000 people and used on a range of projects. A generic FEP database has also been developed by TNO of the Netherlands, but is not public, although several summary papers have been published. The database has been developed through several phases, and the most recent version is CASSIF (e.g. Yavuz et al. [12]).

The FEP descriptions in Quintessa's on-line Generic CO_2 FEP Database were chosen for their relevance to the long-term safety and performance of the storage system after CO_2 injection has ceased, and the injection boreholes have been sealed. FEPs associated with the injection phase are included where these can affect long-term performance and the status of the system at closure. Each FEP entry in the database comprises a description and explanation of the FEP's relevance to the system's long-term safety and the performance. References to relevant publications and websites are also provided (Fig. 1).

3. The FEP Database Developed for RITE, the RITE-DB

The RITE-DB (Fig.1) is based on Quintessa's CO_2 on-line FEP database, but unlike Quintessa's database it has two components:

Fig. 1. Example entry from the RITE-DB, showing links to sources of information.

- a ‘Reference Database’ of 215 FEPs, which is fundamentally the 178 FEPs in the version of Quintessa’s on-line generic FEP database that existed at the end of 2005 when the RITE-DB was developed, plus another 37 FEPs that explicitly describe phenomena of particular relevance to Japan (active faults, active folding, onsen etc).
- a ‘General Database’ of FEPs that consists of all FEPs in the Reference Database plus additional FEPs that were identified during the evaluation of some hypothetical Japanese sites. These additional FEPs can all be mapped (linked) to FEPs in the Reference Database.
- This two-component structure was developed for the RITE-DB, because it preserves a relatively simple and easy-to use standard audit tool (the Reference Database) while at the same time recording all those specific phenomena that individual workers have identified during the course of actual projects (the Reference Database).

The General Database of the RITE-DB contains descriptions of possible general relationships among different FEPs. The software allows a user to select a sub-set of the FEPs from this database to create a site-specific FEP database according to the characteristics of a particular site. The relationships among FEPs are copied from the General Database to the site-specific database. The functionality should be enhanced to make it easier for users to specify relationships among FEPs when generating scenarios.

The RITE-DB contains functionality to generate Process Influence Diagrams (PID’s) to show relationships among FEPs when developing scenarios.

4. Review of Worldwide Applications of FEP Lists and Scenarios Development

4.1. Weyburn, Saskatchewan, Canada

A site-specific FEP list was developed using an expert workshop during the Weyburn Project in Saskatchewan, Canada (Stenhouse et al. [6]). The list was used to: stimulate discussions among experts;

systematically analyse storage systems; identify all relevant system characteristics, phenomena that affect these characteristics and interactions between them; and to provide a basis for describing scenarios. Quintessa's on-line Generic CO_2 FEP Database was used to audit the site-specific FEP list.

Scenarios were developed only during Phase I of the Weyburn Project. The approach involved a systematic systems analysis by groups of experts during workshops and was similar to that undertaken during most projects to develop repositories for radioactive wastes (Stenhouse et al. [6][13]). The following steps were taken: definition of the 'system' to be assessed; development of a list of FEPs which together describe the particular system being studied; differentiation between those FEPs which belong to the system itself and those which can be regarded as external to the system (EFEPs); identification of interactions between these FEPs; construction of scenarios; and description of how the FEP interactions will analysed in the modeling to be undertaken for each scenario.

This stepwise approach produced a list containing 42 'scenario-generating events' (Stenhouse et al. [6]). However, it was considered unnecessary, and indeed impossible to describe all possible scenarios. Therefore scenarios were treated as illustrative examples of future site behavior, following an approach described by Chapman et al. [14]. Scenarios were not defined to be comprehensive or mutually exclusive as no international consensus exists on analyzing the probabilities of scenarios. Instead it was aimed consider a sufficiently large number of scenarios to test safety adequately by addressing both the most likely possible evolutions of the system and less likely futures which have features of possible concern.

4.2. Williston Basin, U.S.A

Analysis of FEPs was undertaken during a risk assessment for possible CO_2 storage in the Williston Basin, U.S.A, following a methodology described by Ayash et al [8], as illustrated in Fig. 2.

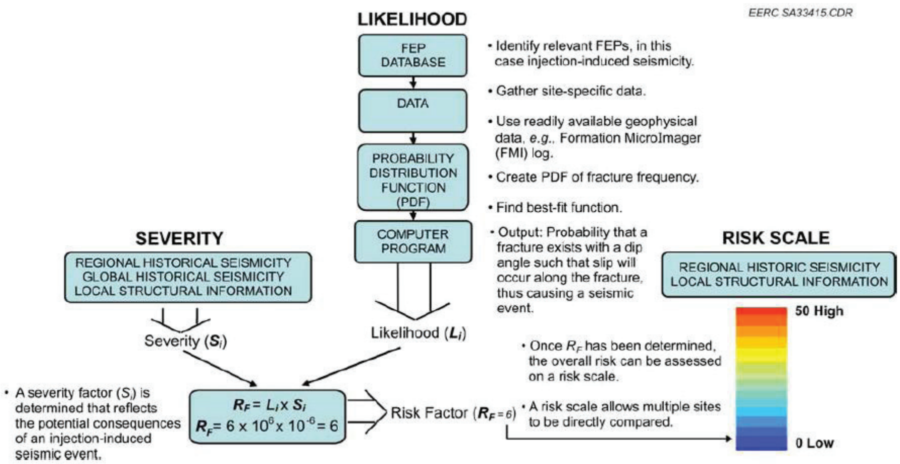

Fig. 2. A flowchart outlining the proposed method for assessing the risk of CO_2 injection-induced seismicity (after Ayash et al., [8]).

Ayash et al. [8] used Quintessa's on-line Generic CO_2 FEP Database as a basis for identifying technical risks. Their basic approach was to evaluate the likelihood of each FEP occurring and the potential consequences of a FEP occurring. They then defined the risk of the FEP, R_{FEP} to be:

$$R_{FEP} = L_{FEP} \times S_{FEP} \tag{1}$$

Where L_{FEP} is the likelihood of the FEP and S_{FEP} is the ‘severity’ or ‘consequences’ of the FEP.

The parameters L_{FEP} and S_{FEP} must be estimated in different ways for different kinds of FEP. The probability of some FEPs, for example the FEP ‘seismicity’, can be estimated by statistical methods using records of seismicity. However, FEPs such as ‘Water management’ cannot be analysed in this way. Furthermore, for different FEPs the concept of ‘severity’ must be defined differently. For example, the severity of seismicity’ in the FEP database can be judged relative to some critical magnitude at which unacceptable damage occurs. In contrast the concept of ‘severity’ has little meaning when applied to FEP ‘Physical properties of CO_2’ on its own. Ayash et al. [8] give only an example of applying their method to ‘Induced seismicity’ and it is unclear how the method has been applied to other FEPs that cannot be treated probabilistically or judged relative to an absolute ‘scale of severity’.

There is no published information about the development of scenarios for long-term performance / safety of CO_2 storage in the Williston Basin, following the end of CO_2 injection (i.e. post-closure). Those scenarios that have been reported concern overall storage scenarios (i.e. storage concepts), including general details of the CO_2 sources, feasibility of transport and storage itself (Steadman et al. [15]).

4.3. Decatur, Project Illinois Basin, U.S.A

FEP lists were used to discuss and record systematically the factors that are potentially important contributors to risk in the Decatur Project in Illinois, U.S.A. These ‘risk FEPs’ were then used as a basis for developing scenarios (Hnottavange-Telleen et al. [9]). The FEPs were evaluated during and after a series of workshops that were attended by up to about 25 experts. Risk was treated similary to Ayash et al. [8], as represented by Equation (1).The likelihood and severity values were each decided by experts on a scale from 1 to 5, thereby representing risks by numbers between 0 and 25. These numerical scales are arbitrary, but allow risks to be evaluated ***consistently.*** The ‘severity’ of each FEP was judged with respect to 5 groups of possible impacts: health and safety; financial; environment; research; and industry viability. The mean risk value specified for each FEP by the expert group was then used to rank the FEP. Risk matrices were used to communicate and compare risks, relative to different project ‘values’ (Fig. 3).

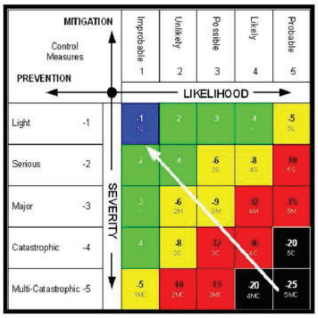

Fig. 3. Risk matrix showing how risks are classified in the Decatur project (after Hnottavange-Telleen et al. [16])

Scenarios were then developed based on the FEPs considered to potentially pose a significant risk. Scenarios were then compiled by the project risk manager.

4.4. Kimberlina Project, U.S.A

The main uses of FEPs during the Kimberlina Project appear to have been (Oldenburg and Doughty

[17]): stimulating discussions among experts; identifying the most important characteristics of the site that influence safety.

There are no public-domain details of scenarios that describe possible future states of the Kimberlina CO_2 storage site. Jordan and Doughty [18] investigated the sensitivity of modelled CO_2 migration to alternative conceptual models for the site's physical characteristics (e.g. models in which the CO_2 storage reservoir was assumed to dip at 7° and models in which there was no dip), and referred to these different conceptual models as 'scenarios'. These 'scenarios' are different from the kinds of scenarios that are typically developed to explore the post-closure evolution of a site and their choice was determined by: uncertainties in information about the site; and the need to build understanding about how the site varies (e.g. to determine the relative significance for CO_2 migration of uncertainties in reservoir dip and uncertainties in fluid viscosity).

4.5. In Salah, Algeria

During the CO2ReMoVe project, FEP lists and databases were used in the performance assessment of the CO_2 storage system at Krechba, In Salah, Algeria (Paulley et al. [19]). An initial systematic analysis of important site characteristics and potential phenomena that influence site behaviour led to the specification of site-specific FEPs. These were used as a basis for structured scenario development. Quintessa's on-line Generic CO_2 FEP Database was used to audit the site-specific FEP list to help ensure that no important characteristics or phenomena had been omitted.

Scenarios for the future post-closure evolution of the Krechba CO_2 storage system were developed at two expert workshops (Paulley et al. [19]). Expert judgements made during structured discussions led to the definition of: (1) a 'normal evolution scenario', consisting of descriptions of the key FEPs and EFEPs identified as relevant to describing the 'best estimate' description for the site and its evolution; and (2) hypothetical alternative evolution scenarios or scenario variants, which were specified to bracket the envelope of potential site performance consistent with uncertainties concerning the overall evolution of the system. Three alternative scenarios that were analysed in detail were: (1) well seal failure; (2) fracturing of the caprock; and (3) over-filling. The alternative scenarios and scenario variants represent: alternative potential representations of key FEPs and interactions between them; and/or reflect conceptual uncertainties associated with the potential impact of EFEPs on the process system. The relative likelihood that each alternative evolution scenario occurs compared to the 'normal evolution scenario' was not quantified. However, the experts agreed that the alternatives should be regarded as 'less likely' to occur than the 'normal evolution scenario'.

4.6. Northern German Projects, Germany

Public-domain details of FEP lists and FEP analysis were produced during the Schweinrich Project in northern Germany (Chadwick et al. [20]; Kreft et al. [21]). In this project, generic FEP lists were used to: (1) stimulate discussions among experts; and(2) build scenarios, by selecting and combining relevant FEPs. The term 'scenario' was used in two different senses (Chadwick, [20]): (1) to describe alternative assumptions about site characteristics, made when undertaking initial site screening; and (2) to describe plausible but hypothetical future evolutions of the site following closure.

There was no FEP analysis during the site screening phase. Alternative scenarios of the first kind described the nature of the storage reservoir and were developed to bound the likely storage capacity. The methodology used is not reported, but appears to have been based on expert judgement. The scenarios developed during site screening: (1) a scenario that assumes an intra-reservoir claystone to be somewhat permeable and hydraulic connection of the two reservoir units; and (2) a scenario in which the claystone is assumed to be impermeable to CO_2. Each scenario had different spill points causing the estimated storage capacity to vary between 1800 Mm^3 (first scenario) and 3000 Mm^3 (second scenario).

Subsequently, an initial performance assessment focussed on the safety of the system, with FEP analysis and 'safety scenario' development following the approach shown in Fig. 4a (Chadwick et al. [20]; Kreft et al. [21]). The FEPs were screened using the generic databases and only FEPs that may occur within a period of 1000 years were considered. However, the impact of these FEPs were modelled over a period of 10,000 years. An important aspect of the methodology was that FEPs were selected and analysed separately for each 'spatial domain' of interest (Fig. 4b).

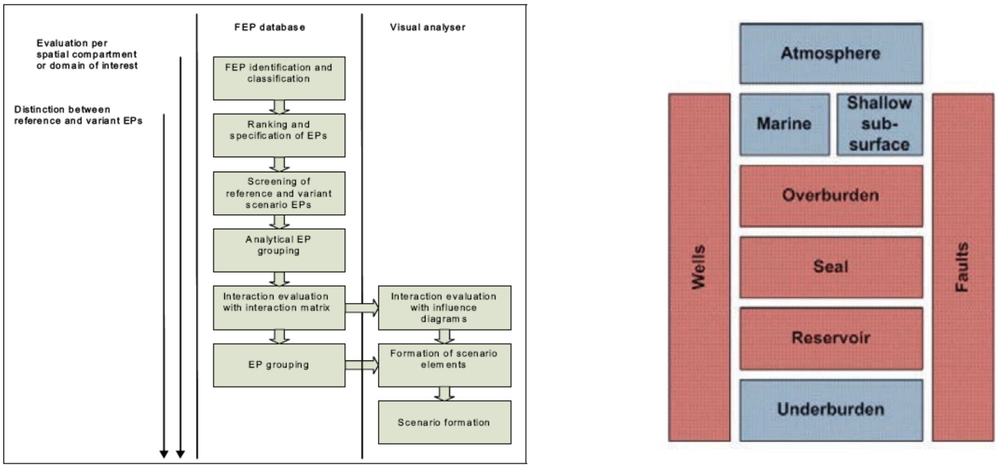

Fig. 4. (a). Steps in the FEP analysis and scenario generation used during the Schweinrich project (after Chadwick et al. 2007[20]). (b). Schematic illustration of the spatial domains considered during the FEP analysis methodology developed by TNO (Wildenborg et al. [2]), with the spatial domains analysed during the Schweinrich study highlighted in red.

The case-specific FEPs were ranked and features, which are static site characteristics, were distinguished from events and processes (EPs), which are dynamic. The following aspects of each EP were evaluated: how the EP is interpreted, for example its safety-relevance; the semi-quantitative probability of its occurrence; and potential impacts if the EP occurs. Groups of EPs with common characteristics were then considered together, based on criteria derived from information in the FEP databases (Wildenborg et al. [2]). The EPs were grouped into geochemical EPs acting over long time-scales (~1000 years), and geomechanical EPs, with both short and long durations. The latter EPs all relate to a leaking fault, whereas the geochemical EPs relate to both a leaking fault and leaking seals.

Scenarios specified as a result of this analysis are: (1) a 'reference scenario', in which CO_2 containment does not fail; (2) a 'leaking seal scenario', in which the seal fails due to CO_2 reacting with the caprock; (3) a 'Leaking well scenario', in which the seals within an existing old well are assumed to fail; and (4) a 'Leaking fault scenario', in which an initially sealed fault is assumed to cut the caprock and subsequently unseal, thereby allowing escape of CO_2. The first of these scenarios is expected to occur, but the probabilities of the other scenarios occurring was not quantified. Instead each one was evaluated as a 'worst case' to explore the consequences should the scenario actually occur.

4.7. Kalundborg, Denmark

A site-specific FEP list was developed during the Kalundborg Project in Denmark (Chadwick et al. [20]; Larsen et al. [22]). The main purposes were: to stimulate discussions among experts; and to provide a basis for describing scenarios. In this project, the term ‘scenario’ was used in two different senses (Chadwick et al. [20]; Larsen et al. [22]): (1) to describe alternative concepts for CO_2 capture, transport and storage; and (2) to describe plausible but hypothetical future evolutions of the site following closure. FEPs were analysed only for the second of these applications. However, no formal scenario development methodology is reported. Instead, expert judgements were used to identify those FEPs that could potentially cause risks to the safety and effectiveness of storage. Groups of related FEPs were defined and potentially these could have been used to develop formal scenarios for assessment. However, there are no published details about this process. It appears that the relatively simple analysis reflects the fact that the project was a feasibility study.

4.8. Valleys, South Wales U.K

A site-specific FEP list was also developed during the Valleys Project in South Wales, U.K. (Chadwick et al. [7],[20]). The aims were again to stimulate discussions among experts; and to provide a basis for describing scenarios.

This project used the term ‘scenario’ in two different senses (Chadwick et al. [7]). One is to describe alternative conceptual models for different aspects of the storage system, principally: CO_2-rock reactions; different spatial distributions of permeable and impermeable strata within the reservoir. The second is to describe plausible but hypothetical post-closure evolutions of the site. FEPs were analysed only in the second case. Expert judgements were used to identify those FEPs that could potentially cause risks to the safety and effectiveness of storage, although the precise methodology has not been reported.

5. Conclusions

FEP analyses of one form or another have been carried out during the safety and performance assessments of a wide range of geological CO_2 storage systems. Two basic approaches have been employed in these analyses: (1) ‘bottom up’, in which scenarios have been developed by combining many FEPs that are identified as being important at a site; and (2) ‘top down’ in which scenarios are developed progressively by identifying a few important FEPs and then describing them in increasing detail. However, the distinction between these two approaches is not clear-cut and most many FEP analyses have combined elements of both approaches. Whatever the approach, generic databases have been used as an audit tool, to help build confidence that no important issues have been missed.

The RITE-DB has the flexibility to be applied to either approach. For example the “Reference database” can be used to support the ‘top-down’ approach, while the “General database” can be used to build scenarios in a ‘bottom-up’ fashion. The ‘Reference database’ is also well-suited as a standard audit tool. The FEP relationships that are in-built to the “General database”, combined with functionality to add new FEP relationships and illustrate all FEP relationships using process influence diagrams (PIDs) where appropriate, means that the RITE-DB has a significantly improved capability to support scenario development. Multiple scenarios, comprising descriptions of FEPs and their inter-relationships, can be stored within the RITE-DB for multiple sites, allowing an audit trail to be maintained.

Acknowledgements

This work was supported by Ministry of Economy, Trade, and Industry of Japan under the contract for “Research and Development of Underground Storage for Carbon Dioxide”.

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